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LOW-THRUST CHEMICAL ORBIT TRANSFER PROPULSION

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Table 4 should be replaced by the following table:

TABLE 4. - TECHNOLOGY REQUIREMENTS FOR LOW-THRUST CHEMICAL PROPULSION

Parameter	Requirement	Reference
Thrust	100 to 1000 lb	Figure 8
Operating Time	5 to 50 hr	Figure 8
Earth-GEO Time	Perhaps 10 days	
Multiple Restarts	Perhaps 10	Figure 3
Specific Impulse	350 to 460 sec	Figure 8
Mass Fraction	0.85 to 0.95	Figure 8
"Soft" Start/Stop	TBD	Figure 9
Throttling for Const. Accel.	TBD	Figure 3
Propulsion System Density	10 to 15 lb/ft^3	Figure 7
Total Impulse	20×10^6 lb-sec	From figure 8

In figure 1, the value 2.69 should be changed to 2.6 g's, and the value 0.019 should be changed to 0.01 g.

LOW-THRUST CHEMICAL ORBIT TRANSFER PROPULSION

by

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E-059

ABSTRACT

The need for large structures in high orbit is discussed in terms of the many mission opportunities which require such structures. Mission and transportation options for large structures are presented, and it is shown that low-thrust propulsion is an enabling requirement for some missions and greatly enhancing to many others. A general comparison of electric and low-thrust chemical propulsion is made and the need for and requirements of low-thrust chemical propulsion are discussed in terms of the interactions that are perceived to exist between the propulsion system and the large structure.

LARGE STRUCTURE, HIGH ORBIT MISSIONS

Need and Realization

Many mission opportunities during the Shuttle era have been identified which are based on large structures in High Earth Orbit (HEO), typically Geosynchronous Earth Orbit (GEO). These missions, whose opportunities commence in the late 1980's, will provide narrow-bandwidth information transfer and communications, earth monitoring, and multi-function platforms, all of which require structures that are much larger than the dimensions of the Orbiter's cargo bay, thereby necessitating assembly and/or deployment from a packaged state. In recognition of these mission opportunities and the resulting need for technology for such large structures, NASA initiated the Large Space Systems Technology (LSST) Program as a multicenter, \$27M new start in FY 79. The SAMSO/Space Based Radar (SBR) mission has been characterized more than the other LSST-type missions by virtue of the \$1.5M total spent recently by SAMSO on study contracts with General Dynamics and Martin Marietta (refs. 1 and 2).

If these mission opportunities are to be realized, they must be affordable. In particular, the number of Shuttle launches required to deliver the structure to Low Earth Orbit (LEO), including the mass of

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the propulsion system required to raise the structure to HEO, must be minimized. This requires efficient (low volume) launch packaging of the structure and low structure mass, so as to permit maximum structure area to be delivered per Shuttle launch.

Mission Strategy Options for Large Structures

The structure and its orbit transfer propulsion system will be transported to LEO in the orbiter, with the structure in a packaged condition. There are two basic options for assembly, deployment, check-out, and placement of the structure in HEO. The first option is to assemble, deploy, and check out the structure in LEO near the orbiter, using the assistance of the Shuttle crew and equipment. In this option, the structure is then transferred in the deployed condition to HEO using the orbit transfer propulsion system. This is the most attractive and likely option because the structure can be brought to a deployed, functional condition using the men and equipment that will routinely exist with the Orbiter, prior to committing the structure to HEO. In some cases, the structure may be so large as to require independent transfer of deployed structural sections, followed by rendezvous and remote docking of these sections in HEO. The second option is to transfer the structure to HEO in a packaged condition, and then assemble, deploy, and check out the structure using fully automated or man-assisted procedures. It is felt, however, that assembly and deployment of large space structures will be far too complex to be accomplished automatically. Typical structures, such as the SBR, may be 600 feet or more in diameter and deployed from a package of about 30 feet long by 15 feet in diameter. Furthermore, equipment for automated assembly or deployment in HEO is likely to be heavy and expensive. Man-assisted assembly and deployment in HEO is not expected because it is unlikely that there will be men in HEO during the time period in which large space structures are first required, and possibly not for a long time thereafter.

Low-Thrust Propulsion Considerations

Transfer or large deployed structures from LEO to HEO introduces the need for reduced thrust to prevent a large structure mass penalty from occurring. The mass penalty consists of additional structure needed to withstand the loads produced by high acceleration during orbit transfer. Figure 1 illustrates the extent of this mass penalty as a function of structure size for two levels of applied acceleration. These data were obtained from information in reference 1 for the aforementioned SBR mission. For an applied acceleration of 2.6 g, typical of Inertial Upper Stage (IUS) acceleration, structure mass increases rapidly with structure size, specifically because of the extra structural material that is needed to prevent failure under acceleration-induced stress. If instead, the applied acceleration is limited

to 0.01 g, the structure mass increases more slowly with structure size. For example, for a structure size of 250 feet, the structure mass could be more than 19 000 pounds if the applied acceleration is 2.6 g, but only about 3000 pounds if the applied acceleration is 0.01 g. The mass penalty of 16 000 pounds in GEO is greatly magnified when the additional propellant mass required to raise the structure from LEO to GEO is taken into consideration: The cost of the Shuttle launches required to lift the additional structure mass and propellant mass to LEO, together with the extra orbit transfer stages required, would be at least $80M.

The bars in the lower part of figure 1 display the size distribution of structures for 49 missions to HEO, identified by Boeing under contract NAS3-21346 (ref. 3). Boeing identified these missions from the literature as part of a study to define the technology advances for electric propulsion for future orbit raising transportation. These mission opportunities occur over the next two decades, and therefore would use the Shuttle. The structures for these missions range in size from a few feet to hundreds of feet. The benefits of low thrust for these missions are also shown. Low thrust propulsion can be used for any or all of the missions. For small size payloads, up to about 60 feet in size, there is no significant benefit in mass or cost due to low thrust. For structure sizes in the 100- to 150-foot range, the cost benefit is moderate; for structures in the 200- to 400-foot range, the cost benefit is major, exceeding $100M per mission at 300 feet. For very large structures, 600 feet and larger, the use of low thrust is enabling. The SBR mission falls into this latter category. Table 1 shows examples of missions in each indicated size range.

Characteristics of Candidate Low-Thrust Propulsion Options

Table 2 shows the characteristics of low-thrust chemical and Solar Electric Propulsion Systems (SEPS). With chemical propulsion, the trip time is relatively short. In contrast, SEPS produces trip times in excess of one hundred days which results in lengthy exposure of the spacecraft to the Van Allen belts. A range of specific impulse of 350-450 seconds is possible with chemical propulsion, which is sufficient, as will be discussed later. For SEPS, the specific impulse is very high, 1500 to 10 000 seconds, which yields high payload fractions and admits the possibility of returning the stage to LEO for reuse, or even returning the structure to LEO for repair or maintenance. For chemical propulsion, acceleration can be made low enough (about 0.01 g) to minimize or eliminate the effect on structure mass. Acceleration produced by SEPS is at least an order of magnitude lower, which is more than low enough to transport large deployed structures.

Figure 2 shows the estimated capability of several propulsion options compared to the large space structure characteristic. Most of the information on this figure was produced in the SBR mission study in

reference 1. The solid curves show the structure mass as a function of maximum applied acceleration for structure areas of 11 000 and 220 000 square feet.* For the larger area, structure mass is greater and increases much more rapidly with acceleration. The curve shows that structure mass approaches its minimum value only if the applied acceleration is reduced below about 0.001 g. However, the SBR studies also indicated that the theoretical minimum structure mass was most likely not achievable, but instead, for accelerations below 0.01 g, other factors such as on-orbit control stiffness or thermal effects would predominate, preventing further structure mass reductions.

The figure also shows the deliverable payload mass (single Shuttle flight) and acceleration for several chemical and SEPS concepts. For the IUS, deliverable structure area is only about 10 000 square feet because of high acceleration and relatively low payload mass capability. For Centaur, deliverable structure area is somewhat greater than IUS because of greater mass capability and slightly reduced acceleration. The P.I. and T.I. data points represent Centaur capability with its RL-10 engines operating at pumped idle and tank-head idle, respectively, and is based on a multiple-burn trajectory that is designed to reduce gravity losses. Note that these P.I. and T.I. versions of Centaur provide a moderate increase in the deliverable area compared to the developed Centaur, even though the deliverable payload mass has been reduced.

The low-thrust hydrogen-oxygen (H/O) and low-thrust hydrocarbon capabilities shown are based on new chemical propulsion technology which provides a specific impulse analogous to much higher thrust systems, a start burn mass of 60 000 pounds, and a multi-burn trajectory. Note that if the low-thrust H/O stage were available, a structure area in excess of 220 000 square feet could be delivered with a single Shuttle flight. The low-thrust hydrocarbon stage would deliver slightly lower area because of reduced payload capability but would provide more room in the Orbiter's cargo bay because of the higher density of hydrocarbon fuels compared to hydrogen. A 50 kW SEPS can deliver very large areas (dashed line on the left) but the trip times are long, at least 200 days for a 220 000 square foot array. The performance of SEPS is

*Additional information on large space structure mass as a function of acceleration is contained in references 2 and 4. The limited amount of information available shows that the mass-acceleration relationship will change, sometimes significantly, as the structural concept changes. The reference 1 information, used in figure 2, was selected because it represented the widest range of structure sizes and because it contained mass-acceleration relationships that seemed typical of large space structures. The results presented in the remainder of this paper are also based on the reference 1 information. These results will require updating as more comprehensive large space structure information becomes available.

shown as a line rather than a point because, with SEPS, it is possible to trade trip time (propulsive energy from a constant power source) with payload mass. Note that, even when the payload is zero, the SEPS trip requires 60 days.

The figure clearly displays the strong interaction between acceleration, structure mass, and area. An acceleration level of 0.01 g enables a 20-fold area increase per Shuttle flight over IUS. This has eliminated consideration of IUS as a propulsive stage for the SBR mission (refs. 1 and 2). It is clear that new low-thrust chemical propulsion technology can provide a very desirable capability to accomplish missions such as the SBR.

The assumed characteristics of the Centaur and the low-thrust H-O and hydrocarbon propulsion systems discussed above are given in table 3.

LOW-THRUST CHEMICAL PROPULSION

Propulsion/Mission Relationships

In addition to the aforementioned large structure mass, area, and acceleration relationships, there are other relationships between low-thrust chemical propulsion and large structure missions. It will be important to use these relationships, discussed below, to evaluate various low thrust chemical concepts from a standpoint of mission effectiveness, and thereby to identify the propulsion technology advancements of maximum benefit.

Mission energy. - Figure 3 shows the velocity increment (ΔV) from LEO to GEO as a function of initial acceleration (a_o) for various number of perigee burns. The lower four curves indicate constant thrust propulsion such that, as the propellant empties from the system, the acceleration increases. The final acceleration, being the maximum acceleration, is the structurally limiting criterion. The ratio between final and initial acceleration increases as specific impulse decreases and ΔV increases. The range of this ratio is from about 2.6 to about 6.7 for chemical propulsion systems operating over the LEO to GEO velocity increments in the figure. Note in the figure that the ΔV tends to increase as the initial acceleration is decreased. This means that either the specific impulse or the propellant mass must be increased in order to retain the same payload mass. Further note that the ΔV increase is significantly less pronounced if the number of perigee burns is increased. For example, increasing the number of perigee burns from 1 to 8 permits an acceleration reduction from 0.03 g to 0.002 g with no attendant ΔV increase. Such action would raise the travel time from 9 hours to about 70 hours, which is still several orders less time than with SEPS.

The uppermost curve indicates constant acceleration propulsion, wherein the thrust is continuously varied (decreased) to compensate for the exhausted propellant. For a given initial acceleration, the constant acceleration trajectory requires greater ΔV than the constant thrust trajectory; however, for a given final (maximum) acceleration, the constant acceleration trajectory requires less ΔV. Constant acceleration (throttled) propulsion concepts are, however more complex than constant thrust concepts, a benefit/cost relationship which needs further study.

Mission economics. - Figure 4 compares the performance of expendable (one-shot) and reusable (fly-back) low-thrust chemical propulsion systems for large cargo delivery to GEO. Earth-to-GEO transportation cost is shown as a function of specific impulse. Assumptions with regard to reusable propulsion system cost and performance were chosen to be realistically optimistic. Neverthelss, the results show that an expendable low-thrust chemical propulsion system is more cost effective than a reusable system for obtainable values of specific impulse. If an expendable stage is used, hydrogen-oxygen propellants result in the lowest earth-to-GEO cost (because of high specific impulse), but hydrocarbon propellants are also competitive. Storable bipropellant systems (specific impulse of about 310 sec) are only marginally competitive because of the disproportionate increase in propellant mass required in LEO for the mission, compared to higher specific impulse systems. Monopropellant systems, such as the teleoperator, are not competitive because of very low I_{sp}.

Mission performance. - Figure 2 showed that the structure area-to-mass ratio increased with decreasing thrust and figure 3 showed that mission ΔV increased with decreasing thrust-to-mass ratio. The inference is that a tradeoff exists. This information has been factored into figure 5. In this figure, specific impulse required to deliver various constant values of structure area (solid lines) is shown as a function of thrust. The figure further assumes a start mass of 60 000 pounds (single Shuttle), a propellant mass fraction of 0.85 (typical of upper stage state-of-the-art), a nine burn trajectory, and constant thrust.

Note that an area-optimum thrust exists for a given specific impulse. For instance, if the specific impulse is 460 seconds, a thrust of about 200 pounds delivers the largest area, about 250 000 suqare feet. If the thrust is increased from 200 pounds at constant I_{sp}, the area decreases because of structure mass penalties produced by higher acceleration. If the thrust is decreased from 200 pounds, the area again decreases, but now because of reduced delivered payload mass capability resulting from higher mission ΔV. The need for a low-thrust, high specific impulse combination of propulsion characteristics is quite clear in figure 5: Delivery of 250 000 square feet of structure area at 200 pounds of thrust requires 460 seconds of specific

impulse. a realistic technology objective. Delivery of the same area at thrust in excess of 3000 pounds would require at least 600 seconds of specific impulse, which is unrealistic. Note that the area optimum thrust (locus of minima from the constant area lines) increases as specific impulse decreases, ranging from 200 pounds thrust at 450 seconds specific impulse to 600 pounds thrust at 300 seconds specific impulse.

Figure 6 again shows specific impulse as a function of thrust for various constant values of deliverable structure area (solid lines), but dashed lines have been added which denote constant deliverable mass. This figure shows the contrast between desired propulsion system characteristics for area delivery and for mass delivery. For area delivery, the desired propulsion system characteristics are in the shaded area on the left, and for mass delivery, they are in the shaded area on the right. Points (A) and (B), one in each shaded area, are representative of the propulsion characteristics in each area. While points (A) and (B) are shown at the same specific impulse, the thrust at (A) is two orders of magnitude less than point (B)(200 lb vs. 20 000 lb). On a delivered area basis, point (B)(80 000 sq ft) represents a 70 percent decrease in performance compared to point (A) (250 000 sq ft), whereas on a delivered mass basis, point (A)(14 000 lb) represents only a 20 percent decrease compared to point (B)(17 000 lb). The figure shows that low thrust propulsion is less penalizing to missions that are not thrust sensitive than high thrust propulsion is to missions that are thrust sensitive, if specific impulse and mass fraction currently available at high thrust can be made available at low thrust.

Cargo Mass and Volume Criteria

The Shuttle Orbiter represents the basis for large structure missions for the next several decades. Because of this, it is necessary to establish its present and future capabilities and limitations as criteria which will influence the desired low-thrust chemical propulsion characteristics. The volume of the Orbiter's cargo bay is 10 600 cubic feet. The mass that it can deliver will most likely increase with time. If this growth ranges from perhaps 40 000 pounds in the near term to perhaps 80 000 pounds as growth Shuttles become operational, minimum allowable cargo density to deliver maximum payload weight will vary between 3.8 pounds per cubic foot (near term) to 7.6 pounds per cubic foot (far term). In the SBR mission studies, the packaged densities of the large radar structures in the cargo bay were approximately 2.5 pounds per cubic feet, such that an Orbiter which carried nothing but packaged SBR would be volume-constrained (full to the 10 600 cu ft limit, but loaded only to 26 500 lb). Since the SBR requires transportation to GEO and since the density of the orbit-transfer propulsion system would be contrastingly high (10 to 14 lb/cu ft), a more shuttle-effective approach results when the Orbiter's

cargo contains both packaged SBR and a corresponding orbit transfer propulsion system during each Shuttle flight. This strategy was used in the SBR studies.

Figure 7 shows the variation of payload delivered mass with payload packaged density. Three pairs of curves are shown, corresponding to 40 000, 60 000, and 80 000 pound Shuttle capability to LEO (designated as M_O). For each pair, the cargo volume is 10 600 cubic feet. Each pair of curves consists of a curve for RP-O propulsion and a curve for H-O propulsion. These propellants are discussed here because of their contrasting characteristics, not because of any overwhelming advantage they may have over any other propellants with similar characteristics. RP-O systems provide higher density and reduced specific impulse compared to H-O systems. The inflection point on each curve represents the transition from volume constraint (left of inflection) to mass constraint (right of inflection). The intersection of the curves in each pair represents the point at which H-O and RP-O systems can deliver the same payload mass to GEO. Since both propulsion systems provide equal acceleration (~0.01 g max.), the ordinate (payload mass) is also a measure of payload area. RP-O systems deliver more payload mass and area to the left of the intersection and H-O systems deliver more payload to the right of the intersection. At each intersection, RP-O systems are mass constrained and H-O systems are volume constrained; thus the payload mass and area delivered in GEO is invariant to payload packaged density with RP-O systems, whereas with H-O systems, a variation between payload delivered to GEO and payload density exists. Figure 7 shows that H-O propulsion systems could deliver up to 20 percent more payload mass (and area) than could RP-O systems if the packaged payload density is greater than some value. If the packaged payload density is less than this value, RP-O systems could deliver up to 7 percent more mass than could H-O systems. The critical density (pertaining to the above observations) increases as the Orbiter's cargo mass capability increases.

New Technology Requirements

Low thrust chemical propulsion requirements for orbit transfer of large structures represent a combination of characteristics which no existing propulsion system provides. The combined requirements of low thrust, high specific impulse, high propellant mass fraction and long burn time introduce technology considerations unlike any previous experience with chemical propulsion. Figure 8 illustrates these requirements. The graph at the top of figure 8 shows propellant mass fraction as a function of specific impulse. Lines of constant deliverable area (to GEO) are shown for a 200 pound thrust, a 60 000 pound (single Shuttle) initial mass, a 9-burn trajectory, and constant thrust. The shaded area denotes the region where new propulsion technology accomplishment is possible and would provide the capability to deliver large areas to GEO. The left portion of the shaded area is characteristic of RP-O propulsion and the right portion is characteristic of H-O

propulsion. With RP-O propulsion, it should be possible to achieve higher propellant mass fraction (perhaps to 0.95) than with H-O propulsion, as the shaded area shows. The graph at the bottom of figure 8 shows thrust as a function of specific impulse for a propellant mass fraction of 0.85, a 60 000 pound initial mass, a 9-burn trajectory, and constant thrust. The shaded region of interest in this graph includes a line of thrust for maximum area, taken from figure 5. Note that the range of thrust is from 1000 pounds to 200 pounds at 350 seconds specific impulse and from 400 pounds to 100 pounds at 460 seconds of specific impulse. Engine burn time is shown as dashed lines. The burn time is more dependent on thrust than specific impulse, and it varies from 5 hours at a thrust of 1000 pounds and a specific impulse of 350 seconds to 50 hours at a thrust of 100 pounds and a specific impulse of 460 seconds.

Table 4 summarizes the aforementioned low-thrust chemical propulsion requirements and introduces several additional considerations. Thrust, burn time, multiple restarts, specific impulse, and mass fraction are noted on this table as discussed above Total impulse is a product of specific impulse and thrust and is approximately constant at 20-million-pound-seconds over the region of interest shown in the bottom graph of figure 9. The "Earth-GEO Time" of perhaps 10 days indicates the length of time the propulsion system will remain fueled during its life cycle. A small fraction of this time is on the ground, the majority in space. It accounts for the time near the Orbiter while the structure is being deployed and/or assembled and the time for transfer to GEO. Because of this time and the multiple restart requirement, management of propellant losses and acquisition of propellants are important technology considerations. Throttling (modulation of thrust to maintain constant acceleration) would lower the mission ΔV with no increase in maximum acceleration, as was discussed in figure 3. Throttling could consist of adjustment of propellant flow through a single engine or stopping a multiple-engine configuration in a sequential manner. The extent of throttling to maintain constant acceleration is dependent on the ratio of start-burn mass to burn-out mass which is a function of specific impulse. Lower specific impulse produces larger throttling requirements. At 460 seconds specific impulse the throttling requirement is about 3:1. It increases to about 4:1 at 350 seconds specific impulse. Multiple engines may have advantages over single engines besides modulation of thrust. Other reasons include roll control with primary propulsion, redundancy, thrust vector control without engine gimballing, soft start/stop by engine sequencing (discussed below), and the possibility of distributing the thrust throughout the structure. Because of these multiple engine possibilities, the single-engine thrust could be below the range of propulsion system thrust indicated in table 4.

The consideration of soft start/stop stems from the need to control the transient loads between the propulsion system and the structure. These loads are perceived to exist because of the high flexibility

of the large structure. This effect is best illustrated with the simple model shown in figure 9. The payload and propulsion system are shown connected with a spring and a damper at the top of the figure. This simulates the elastic property of the structure. In reality, the system is probably not linear as shown, but the linear assumption is adequate to describe the perceived transient effect. Two simultaneous equations of motion, one for the propulsion system, and one for the payload can be written and solved to produce graphs such as those shown on the bottom of figure 9. On the left, the thrust, F, is assumed to occur instantaneously in time. At this instant, the structure is relaxed (the spring is in its free position) and the acceleration takes place entirely within the propulsion system at a value of F/M_{PS}. At some later time, t, the spring is maximally compressed. A damped oscillation occurs, and eventually the entire propulsion/payload system accelerates at the thrust, F, divided by the total system mass, $M_{PS} + M_{PL}$. The oscillation is at the natural frequency of the structure, which can be very low, perhaps 0.1 Hz or less.

A variable acceleration is produced on the propulsion system as shown, the extent of which is influenced by the mass and elastic properties of the structure and by the mass of the propulsion system. As the propulsion system becomes lighter, such as at ignition for the last burn (apogee), the greatest effect of this sort occurs on the propulsion system. The analysis shows that it is possible to produce negative acceleration on the propulsion system as shown by the shaded portion of the second curve on the left. Should this occur, the propellants could lift off the tank drain ports, with obvious results. The acceleration variations on the propulsion system could also influence the thrust of the propulsion system, thereby creating a low-frequency "pogo"-like effect which could catastrophically amplify the oscillation. A variable acceleration is also produced on the structure as shown on the bottom curve on the left. This transient acceleration may be significantly higher than the steady state acceleration, and therefore it could significantly decrease the structure area and/or increase the structure mass to be transported. A similar transient effect can occur at the end of each propulsion system burn. The obvious way to control these transient effects is to modulate the thrust from the point of ignition as shown on the right graphs. This does not necessarily imply engine throttling (propellant flow rate adjustment). Approaches such as thrust reversing devices similar to those on jet engines or rocket engine pairs which can be gimballed so as to oppose one another may be viable, because the thrust modulating time may be small compared to the burn time; therefore, the amount of wasted propellant may be minimal. The possibility exists that sensors which detect structural deflection would be used in a system which would provide active thrust control during these transient periods.

Other Mission Opportunities

The foregoing discussion of new low-thrust propulsion technology with emphasis on chemical propulsion, was based on the opportunity to use the Shuttle Orbiter and technology for large structures to accomplish a new class of future missions to high orbit. It is important, however, not to constrain the consideration of low-thrust propulsion just to large platforms and the like. It is nearly impossible to cite any example of a spacecraft with a destination orbit higher than LEO that does not have some antenna, boom, solar array, or other appendage that must deploy in order for the spacecraft to function. Traditionally, the deployment is reserved until after the upper stage burn so as to allow the appendage to survive the acceleration produced by this upper stage. Because of this strategy, the deployment mechanism must be highly reliable, therefore expensive, and missions still sometimes fail because deployment fails to take place. Low thrust upper stage propulsion would enable deployment of all classes of high-orbit bound spacecraft prior to upper stage burn and while they are still in the vicinity of the Orbiter, thereby enabling functional checkout and providing manned repair access or return to Earth should the need arise. The unique capability that the Shuttle offers, of providing human operations in LEO and return of spacecraft from LEO to Earth, is capitalized on by a mission strategy which involves deployment and operational checkout of the spacecraft in LEO, a strategy which low-thrust propulsion enables. An example of this would be to use low-thrust chemical propulsion to provide the required hyperbolic excess velocity to a SEPS mission in the solar system with the SEP arrays fully extended beforehand.

CONCLUSIONS

Low thrust propulsion capability is needed which will enable the Shuttle to accomplish future missions which involve the placement of large structures in high earth orbits. For these missions, the criterion of delivered structure area takes precedence over the criterion of delivered mass, which results in the desired low thrust propulsion characteristic. The shorter trip time characteristic (than with electric propulsion) and thrust that is low enough to enable large area makes low thrust chemical propulsion a viable method of accomplishing the orbit transfer of large structures. Low thrust chemical propulsion is far less penalizing to payload mass than is high thrust to payload area, such that low-thrust chemical propulsion may be the best single choice for Shuttle-based orbit transfer propulsion of cargo in general. While the obvious need for low thrust chemical propulsion is for orbit transfer of large structures, it also provides the opportunity to deploy and checkout virtually all spacecraft with high orbit destinations while in the Orbiter's vicinity, a mission strategy option with enormous potential benefit to the mission planner.

Concerning the requirements of low-thrust chemical propulsion itself, the needed combination of low thrust, high specific impulse, high propellant mass fraction, long burn time and multiple restarts are unique and currently not within the state-of-the-art. Transient control of thrust and continuous thrust modulation to limit the acceleration on the payload may also be required.

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3. "Study of Electric Propulsion for Near-Earth Space Missions," Boeing Aerospace Co., Seattle, Wash., D180-24819-1, Oct. 1978.

4. Kunz, K. E., "Implication of Orbit Transfer on Propulsion and Vehicle Configuration for Large Space Systems," AIAA Paper 79-0930, May 1979.

TABLE 1. - EXAMPLES OF FUTURE MISSIONS TO HEO WHICH
INVOLVE STRUCTURES OF VARIOUS SIZES

Mission	Size, ft	Quantity	Opportunity	Destination
Synchronous Meteorological Satellite	30	3	1985	GEO
Energy Monitor Satellite	150	1	1990	GEO
Orbiting Deep Space Relay Station	330	2	1995	22 250 miles, 11° inc.
GEO Communications Platform	1400	5	1990+	GEO

TABLE 2. - LOW-THRUST PROPULSION SYSTEM CHARACTERISTICS
FOR EARTH ORBITAL MISSIONS

Characteristic	Chemical	Electric
Trip time	Short (1 to 3 days)	Long (~100 days or more)
Specific impulse	350 to 450 seconds	High (1500 to 10 000 sec) - yields high payload fractions
Acceleration	Low enough - To minimize effect on structure mass	Very low - Desirable for transportation of large structures

TABLE 3. - CHARACTERISTICS OF CHEMICAL PROPULSION

SYSTEMS SHOWN IN FIGURE 2

		Low Thrust		Centaur		
		H/O	HC/O	St'd.	P.I.	T.I.
T	- Thrust, lb	200	200	30 000	30 000	600
I_{SP}	- Specific impulse, sec	460	370	444	410	390
γ	- Propellant mass fraction	0.88	0.92	0.87	0.87	0.87
M_o	- Startburn mass, lb	60 000	60 000	48 150	45 230	43 420
T/M_o	- Startburn accel., g	0.0033	0.0033	0.62	0.066	0.014
ΔV	- Velocity Inc., ft/sec	15 100	15 100	13 700	14 100	14 450
M_{PL}	- Payload mass, lb	16 420	13 140	14 050	11 130	9320
M_P	- Propellant mass, lb	38 530	43 110	29 700	29 700	29 700
M_F	- Final mass, lb	21 470	16 890	18 450	15 530	13 720
T/M_F	- Final accel., g	0.0093	0.0118	1.626	0.193	0.044

TABLE 4. - TECHNOLOGY REQUIREMENTS FOR LOW-THRUST

CHEMICAL PROPULSION

Parameter	Requirement	Reference
Thrust	100 to 1000 lb	Figure 9
Operating Time	5 to 50 hr	Figure 9
Earth-GEO Time	Perhaps 10	Figure 3
Multiple Restarts	350 to 460 sec	Figure 9
Specific Impulse	0.85 to 0.95	Figure 9
Mass Fraction	TBD	
"Soft" Start/Stop	TBD	Figure 3
Throttling for Const. Accel.	10 to 15 lb/ft^3	Figure 8
Propulsion System Density	20×10^6 lb-sec	From figure 9
Total Impulse	Perhaps 10 days	

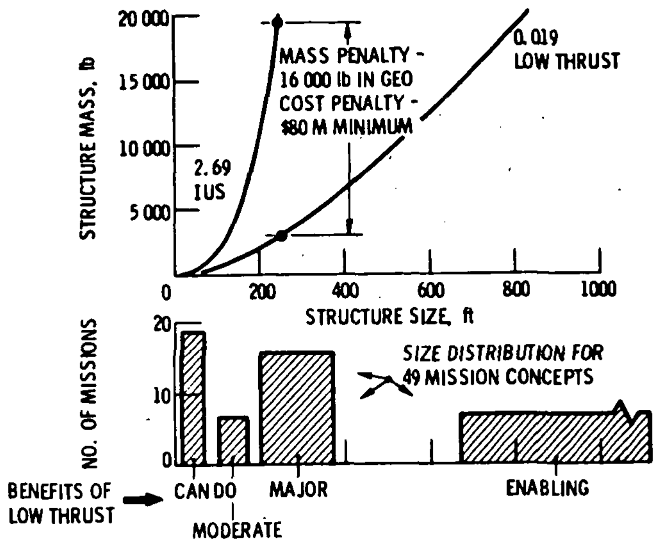

Figure 1. - Effect of propulsive thrust on large structures.

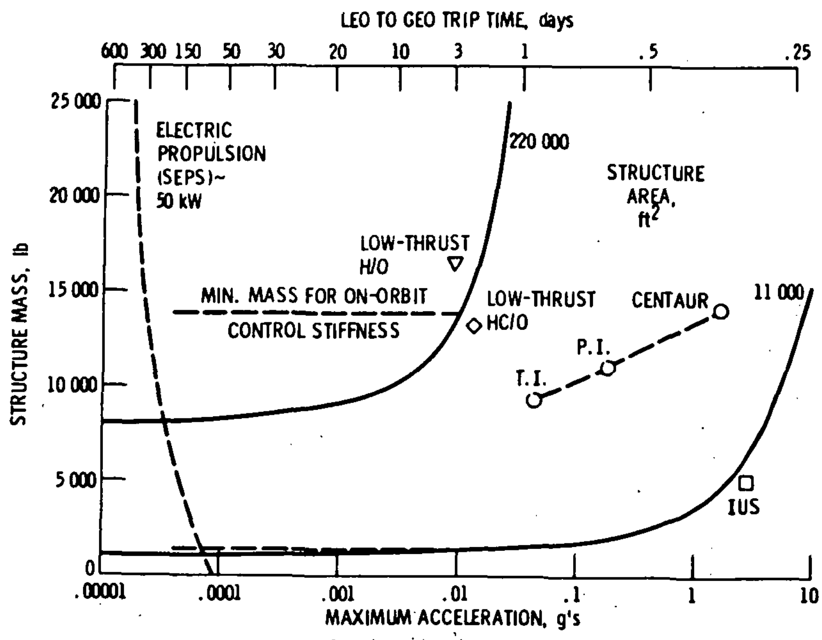

Figure 2. - Effect of acceleration on structure weight - SBR mission.

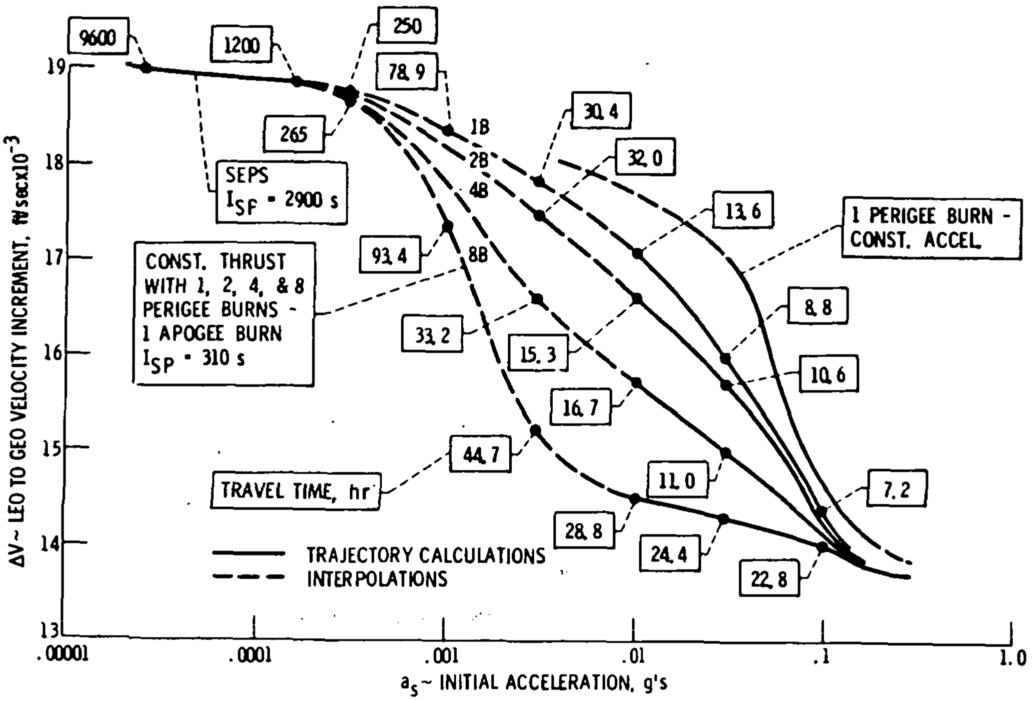

Figure 3. - Trajectory characteristics for low thrust orbit transfer.

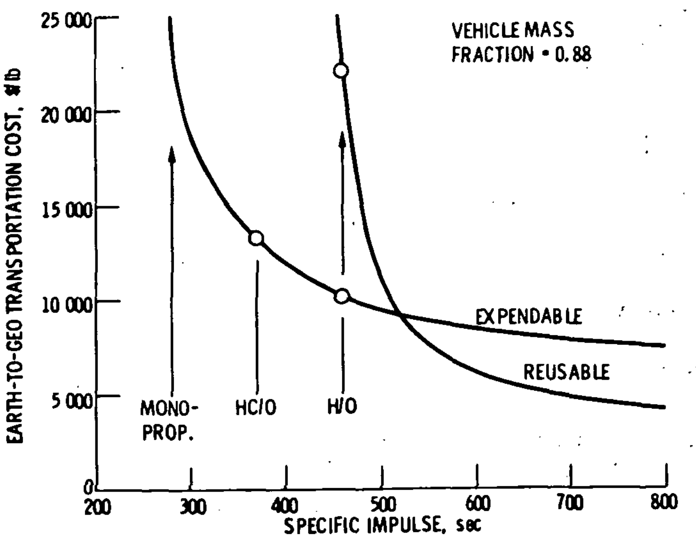

Figure 4. - Economic comparison of expendable and reusable propulsion systems - low thrust LEO-GEO mission.

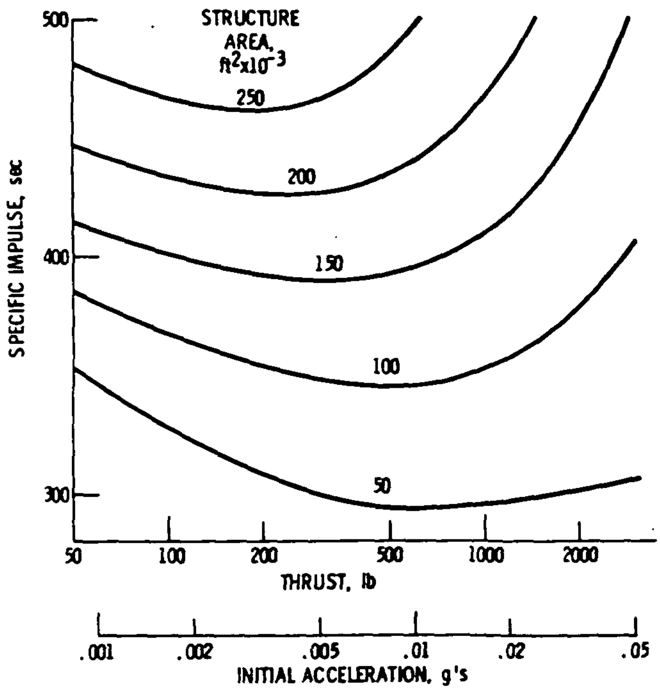

Figure 5. - Area delivered by propulsion systems with various characteristics.

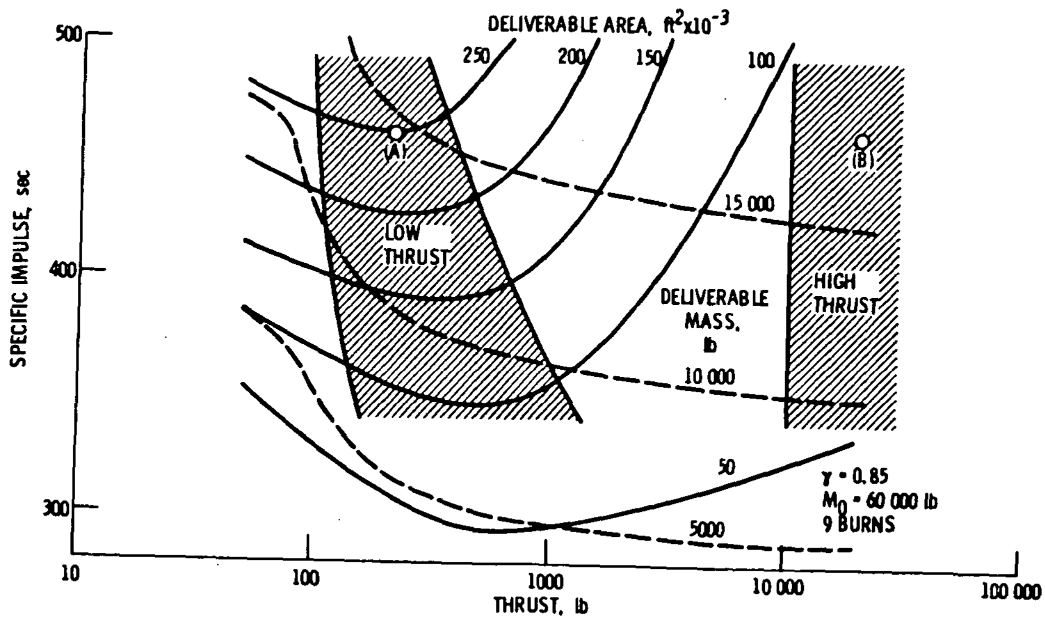

Figure 6. - Contrast between deliverable area and mass from propulsion systems with various characteristics.

	RP/O	H/O
ρ_{STAGE}, lb/ft^3	14.5	10
$\gamma_{PROPELLANT}$	0.93	0.88
I_{SP}, sec	370	460
ΔV, ft/sec	14 700	14 700

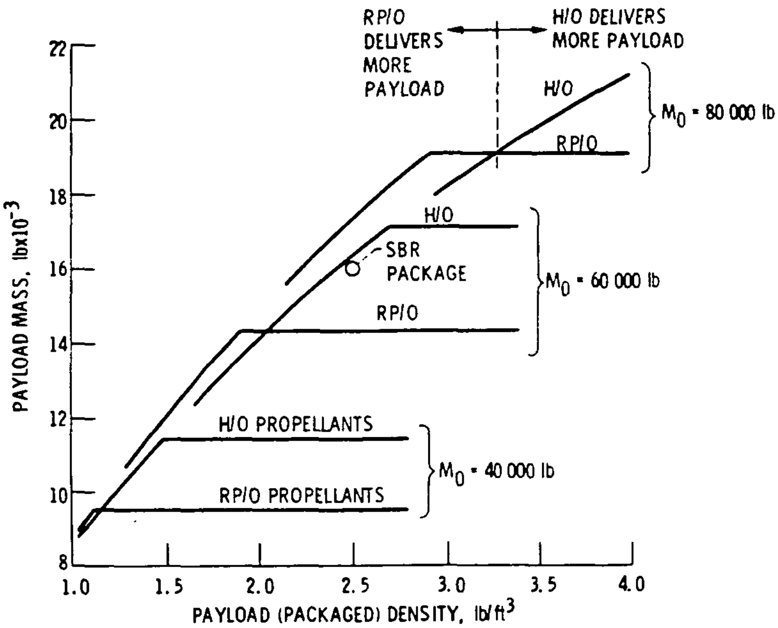

Figure 7. - Deliverable mass variations with payload packaged density.

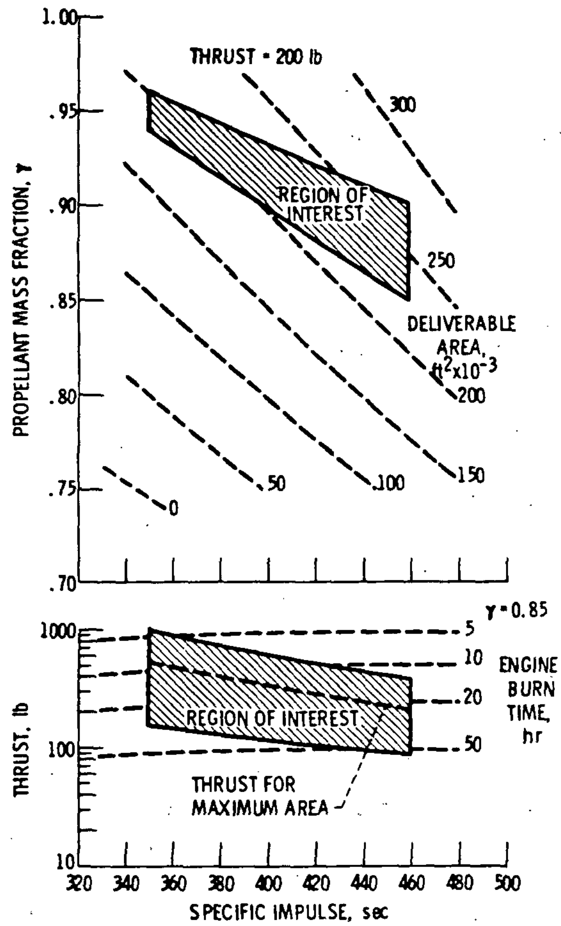

Figure 8. - Low thrust chemical propulsion requirements.

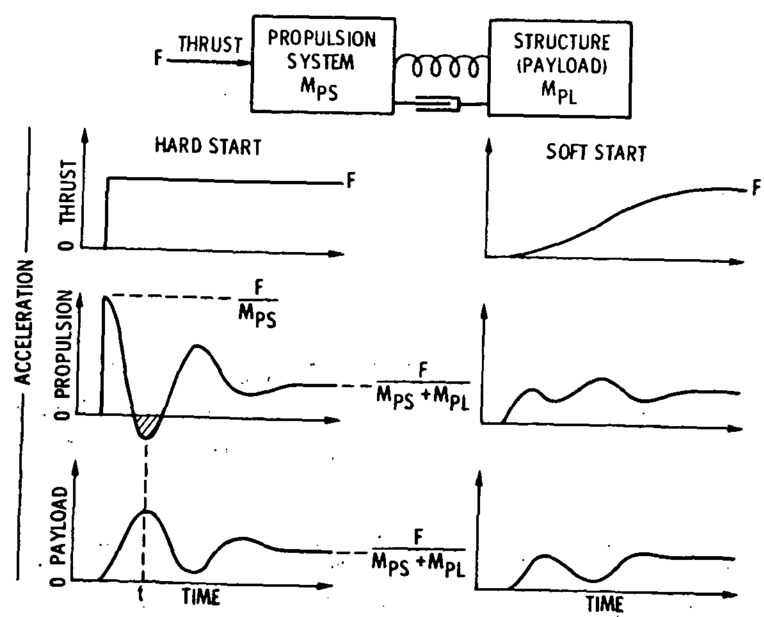

Figure 9. - Soft start/stop effect on transient accelerations.

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15. Supplementary Notes

16. Abstract

The need for large structures in high orbit is discussed in terms of the many mission opportunities which require such structures. Mission and transportation options for large structures are presented, and it is shown that low-thrust propulsion is an enabling requirement for some missions and greatly enhancing to many others. A general comparison of electric and low-thrust chemical propulsion is made and the need for and requirements of low-thrust chemical propulsion are discussed in terms of the interactions that are perceived to exist between the propulsion system and the large structure.

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